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Design of a 3D Gravity Balanced Orthosis for Upper Limb

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Abstract— **This paper describes the design of a gravity balanced spatial orthosis. Previous works introduced planar mechanisms only and neglected friction. They relied on counterweight or auxiliary parallelograms. The main contributions of this paper are: (i) we succeed in designing a spatial (3D) mechanism and (ii) we analyzed the effects of friction. We designed a very simple system made with two pulleys and two springs in order to ensure gravity compensation. The system is in static equilibrium whatever its posture. It has three passive degrees of freedom at the shoulder and two at the elbow. A prototype of this orthosis is presented at the end of the paper.**

Keywords: rehabilitation robotics, orthosis, gravity-balancing.

I. Introduction

An orthotis is an exoskeleton worn by a patient who cannot control anymore the motion of one or several of his/her limbs in a voluntarily manner. This happens for instance to patient suffering from cerebral palsy. It can also be worn by persons having experienced a stroke to recover their strength and mobility, or for those who have control but lack muscular force. Restauring these functions is classically the job of physical and occupational therapists, but since a few years, several prototypes of such devices have been designed and experienced in labs, mainly in the US and Japan [1]. These rehabilitation robots are intended to exercise limbs of patients in order to retrain voluntary movement control or to improve their strength. Only a few commercial devices are available, among which for instance the InMotion robot of Interactive Motion Tech. Inc., the Lokomat from Hocoma, and very recently, the ReWalk from Argo Medical Technologies Ltd.

For many patients with upper limb disabilities, it would be helpful to provide them with an orthotic device compensating for gravity that would allow them to carry out routine functions, such as eating for instance, with their remaining muscle strength. This is the objective of the work presented in this paper.

There are three degrees of freedom (DOF) in the human shoulder and two in the elbow. The mechanisms presented in the literature (see section II) have generally two DOF for the shoulder and one for the elbow (sometimes two). They use a planar mechanism rotating around a vertical axis at the shoulder, which allows the patient to move his hand to wherever location but does not allow him to use all his muscles. The rotation around a vertical axis has no effect on gravity compensation.

The mechanical device that we have developed is completely passive. It makes use of springs and pulleys for gravity balance. In the sequel, by analogy to the human body, we will denote the body next to the frame by "*arm*" and the other one by "*forearm*", the passive joint between the arm and the frame by "*shoulder*" and that between the arm and the forearm by "*elbow*". This mechanism has three DOF at the shoulder and two at the elbow. However, three parameters are enough to describe mathematically the positions of the centers of masses of the arm and the forearm. The device is kinematically redundant. We will make use of significant parameters such as extension of the shoulder elbow and abduction of the shoulder to modelize the orthosis. In the second section, we review previous works presented in this field. In the third section, we present the design of the orthotic device and its mechanical properties. The fourth section is devoted to the analysis of the effects of the friction on the device. Then, we present a numerical application and a CAD study of the device. The paper ends by a conclusion and propositions of further work.

II. Gravity Balancing

A device is said to be gravity balanced if it is in indifferent equilibrium [2]. Mathematically, this condition means that the total potential energy of the device is invariant whatever its configuration. Physically, the potential energy is constant if the centre of mass of the device is inertially fixed. The potential energy can also remain invariant if elastic elements compensate for variations due to the motion of the masses.

The center of mass can be inertially fixed when:

(a) a countermass on each body of the mechanism is used to inertially fix the center of mass of the system [3,4],

(b) auxiliary parallelograms designed from the knowledge of geometry and inertia properties are added to physically determine the center of mass of the device [5].

This procedure is more intuitive but its drawback is that it increases the dynamic inertia of the device, which pushes designers to use elastic elements. Previous works on design with spring balancers may be classified as follows:

(a) Balancing with springs directly connected with links[6-9],

(b) Balancing with cable and pulley arrangement [10-14],

(c) Balancing by using an auxiliary mechanism, which can be a linkage [15-20], a cam [21,22] or a gear train [23,24].

Unfortunately, in the literature most spring balanced mechanisms are planar. In [25], a hybrid methodology for gravity balancing of spatial robotic manipulators is presented. It makes use of auxiliary parallelograms to first locate the center of mass, and springs are also connected to this point to make the potential energy invariant with respect to configuration. This solution can be implemented on a manipulator but not on an orthosis because it is too bulky. A spatial two-DOF serial manipulator was studied for gravity balancing in [25]. The authors proved that for this class of manipulators, the conditions for gravity balancing require that the end points of the springs move relatively to the mechanism, i.e., be independently actuated. This would require extra actuators to be mounted on the system, which is undesirable. These different reasons led us to design a 5-DOF mechanism balanced by two springs.

III. Design of the Balanced Orthosis

The problem has two key issues: the equilibrium of the forearm and the equilibrium in 3D. In fact, in order to balance the forearm, a torque and a force have to be applied at the elbow. The force is constant and equal to the forearm weight. The torque is depending on both the forearm and arm orientations with respect to gravity. Therefore, the problem is to design a mechanism that balances gravity on the forearm whatever the orientation of the arm.

A. *Design of the mechanism*

The bodies (1), (2) and (3) are mounted on a support (0) (figure 1) and connected to it with a spherical joint. The arm (1) and forearm (2) are connected together by a revolute joint R_{j2}. Two springs are used to compensate for gravity.

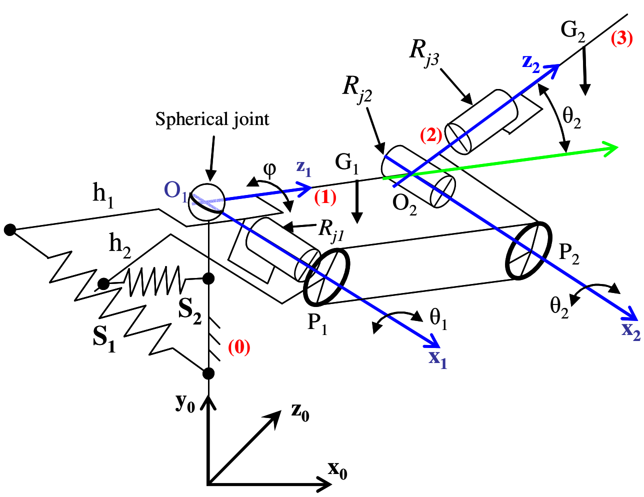

Figure 1:Kinematic scheme of the device and notations

The spring S_1 is used to equilibrate the arm when developing a torque around axis x_1 of the revolute joint R_{j1}. This torque depends on the orientation of the arm and the forearm with respect to gravity. The spring S_2 is used to equilibrate the forearm when developing a torque around axis x_2 of the revolute joint R_{j2}. A pulley P_2 is pinned to the forearm. The other pulley P_1 is connected with the revolute joint R_{j1} to the arm (1) at O_1. The axes x_1 and x_2 of both pulleys P_1 and P_2 remain parallel. The same torque is applied on both pulleys that have exactly the same motion.

The mechanism described so far is planar. In order to provide 3D motion, we introduced a spherical joint at the shoulder. Finally, in order to allow an axial rotation of the forearm, we added a revolute joint R_{j3} along its main axis. Consequently, the suggested mechanism has five degrees of mobility, but relies on two springs to balance gravity. In the following sub-section, we discuss the dimensioning of the springs.

B. *Spring dimensioning*

The total potential energy is invariant if the variation of the gravitational potential energy is equal and opposite to that of the elastic potential energy

The variation of the gravitational potential energy is the work of the device weight during motion. Mathematically, this work is the sum of the product of each weight by the vertical travel of the corresponding center of mass. We use two traction springs with zero initial length (the assembly is shown is the last section), the variation of their elastic potential energy being proportional to the sum of their length squares. We have to locate the centers of mass for both bodies (arm and forearm) and the extremities of the springs in order to developing an analytical expression for elastic and gravitational potential energies. These expressions have to be identical whatever the configuration. The coefficients of each factor have to be the same in both expressions. That allows us to identify the stiffness and to locate the extremities of each spring.

In order to carry out this computation we need three parameters: the extension of the elbow, the abduction and extension of the shoulder. In what follows, let us denote these angles by θ_2, φ and θ_1 respectively. Let $(x_2y_2z_2)$, $(x_1y_1z_1)$ and $(x_0y_0z_0)$ be the coordinate frames associated to the forearm, the arm and the support respectively. The homogeneous transformation matrices between these coordinate frames are:

$$ {}^{2}T_{1} = \begin{bmatrix} \cos\theta_2 & -\sin\theta_2 & 0 & l_1 \\ \sin\theta_2 & \cos\theta_2 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1) $$

$$
{}^{1}T_0 = \begin{bmatrix} \cos\theta_1 & -\sin\theta_1 & 0 & 0 \\ \cos\varphi\sin\theta_1 & \cos\varphi\cos\theta_1 & -\sin\varphi & 0 \\ \sin\varphi\sin\theta_1 & \sin\varphi\cos\theta_1 & \cos\varphi & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}
$$

The homogenous coordinates of G_1 and G_2 in the reference frames ($x_1y_1z_1$) and ($x_2y_2z_2$) respectively are:

$$
\left[O_1G_1\right] = \begin{bmatrix} \frac{l_1}{2} & 0 & 0 & 0 \end{bmatrix}^T,\ \left[O_2G_2\right] = \begin{bmatrix} \frac{l_2}{2} & 0 & 0 & 0 \end{bmatrix}^T \tag{3}
$$

then in frame ($x_0y_0z_0$):

$$
O_1G_1 = \left[{}^{0}T_1\right]\left[O_1G_1\right] = \begin{bmatrix} \frac{l_1}{2}\cos\theta_1 \\ \frac{l_1}{2}\cos\varphi\sin\theta_1 \\ \frac{l_1}{2}\sin\varphi\sin\theta_1 \\ 1 \end{bmatrix}, \left[O_0G_2\right] = \begin{bmatrix} \frac{l_2}{2}\cos\left(\theta_1+\theta_2\right)+l_1\cos\theta_1 \\ \cos\varphi\left(\frac{l_2}{2}\sin\left(\theta_1+\theta_2\right)+l_1\sin\theta_1\right) \\ \sin\varphi\left(\frac{l_2}{2}\sin\left(\theta_1+\theta_2\right)+l_1\sin\theta_1\right) \\ 1 \end{bmatrix} \tag{5}
$$

Let us measure the variation of the gravitational potential energy between the initial configuration $\theta_1=\pi/2$, $\theta_2=\varphi=0$ and an arbitrary configuration. The variation is:

$$
\begin{aligned}
\Delta E_P &= \left(m_1\Delta y_{G_1} + m_2\Delta y_{G_2}\right)g \\
&= \left[m_2\left(\frac{l_2}{2}+l_1-\cos\varphi\left(\frac{l_2}{2}\sin\left(\theta_1+\theta_2\right)+l_1\sin\theta_1\right)\right) + m_1\frac{l_1}{2}\left(1-\cos\varphi\sin\theta_1\right)\right]g
\end{aligned} \tag{6}
$$

Let f_1 and f_2 be the coordinates of the fixed extremities of the first and second springs respectively:

$$
f_1 = \begin{bmatrix} u_1 \\ v_1 \\ 0 \end{bmatrix}, f_2 = \begin{bmatrix} u_2 \\ v_2 \\ 0 \end{bmatrix} \tag{7}
$$

The coordinates of the moving extremity of the first spring, denoted as $f_{1'}$, is:

$$
f_{1'} = \begin{bmatrix} -h_1\cos\theta_1 \\ -h_1\cos\varphi\sin\theta_1 \\ -h_1\sin\varphi\sin\theta_1 \end{bmatrix} \tag{8}
$$

On the other hand, we know that vectors $\left[O_2G_2\right]$ and $\left[O_0f_{2'}\right]$ are always parallel. In order to get the coordinates of G_2, we have to replace l_1 by 0 and $l_2/2$ by $-h_2$ in $\left[O_0G_2\right]$, yielding:

$$
f_{2'} = \begin{bmatrix} -h_2\cos\left(\theta_1+\theta_2\right) \\ -h_2\cos\varphi\sin\left(\theta_1+\theta_2\right) \\ -h_2\sin\varphi\sin\left(\theta_1+\theta_2\right) \end{bmatrix} \tag{9}
$$

Then, the variation of the elastic potential energy is:

$$
\begin{aligned}
\Delta Ep_s &= \frac{1}{2}\left(k_1\overline{f_{1'}f_1}^{\,2} + k_2\overline{f_{2'}f_2}^{\,2}\right) \\
&= \frac{1}{2}\begin{pmatrix} k_1\left(u_1^2+v_1^2+h_1^2+2u_1h_1\cos\theta_1+2v_1h_1\cos\varphi\sin\theta_1\right) \\ +k_2\left(u_2^2+v_2^2+h_2^2+2u_2h_2\cos\left(\theta_1+\theta_2\right)+2v_2h_2\cos\varphi\sin\left(\theta_1+\theta_2\right)\right) \end{pmatrix}
\end{aligned} \tag{10}
$$

The identification of equations (6) and (10) gives:

$$
\begin{aligned}
&u_1 = u_2 = 0 \quad k_1 = \frac{m_2+2m_1}{2h_1^2}gl_1 \\
&v_1 = -h_1 \\
&v_2 = -h_2 \qquad k_2 = \frac{m_2}{2h_2^2}gl_2
\end{aligned} \tag{11}
$$

The stiffness of both springs is independent of arm and forearm configurations. As indicated in equation 11, k_1 and k_2 are function of the lever arms h_1 and h_2. For constant h_1 and h_2, k_1 and k_2 are constant. We can therefore make use of two linear springs. The system will be in indifferent equilibrium. Moreover, three parameters are enough to describe the configuration of the device. Indeed, the rotation around the y_0 have no effect on the weight balancing.

C. *Balancing forces in the spherical joint*

The device is in indifferent equilibrium. This means that the mechanism is in static equilibrium whatever the posture of the arm. In order to dimension the components, we compute the internal loads. The most sensitive parts are the passive joints. A spherical joint is free of torques, however it is subject to variable forces.

The spherical joint is the only connection between the device and the frame. The force applied on the spherical joint is the resultant of the loads applied on both rods. These forces are the weight and the spring tensions.

$$
\sum\vec{F} = \left(m_1+m_2\right)\begin{bmatrix} 0 \\ -g \\ 0 \end{bmatrix} + k_1\begin{bmatrix} h_1\cos\theta_1 \\ -h_1+h_1\cos\varphi\sin\theta_1 \\ h_1\sin\varphi\sin\theta_1 \end{bmatrix} + k_2\begin{bmatrix} h_2\cos\left(\theta_1+\theta_2\right) \\ -h_2+h_2\cos\varphi\sin\left(\theta_1+\theta_2\right) \\ h_2\sin\varphi\sin\left(\theta_1+\theta_2\right) \end{bmatrix} \tag{12}
$$

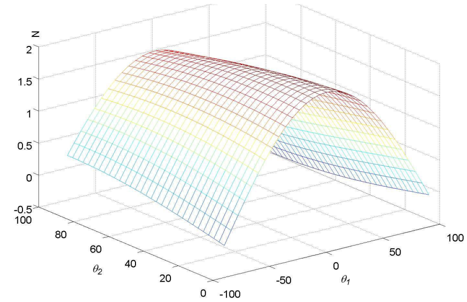

Figure 2: Force along the x_0-axis(*N*), angles are in deg

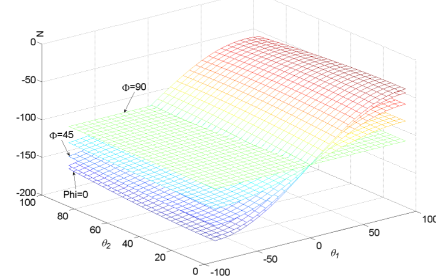

Figure 3: Vertical force (*N*), angles are in deg

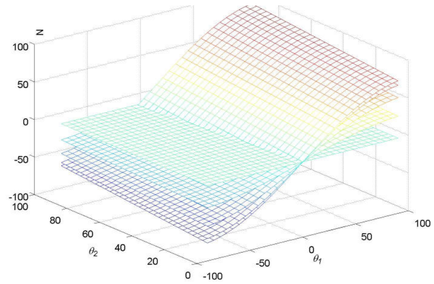

Figure 4: Force along the z-axis (*N),* angles are in deg

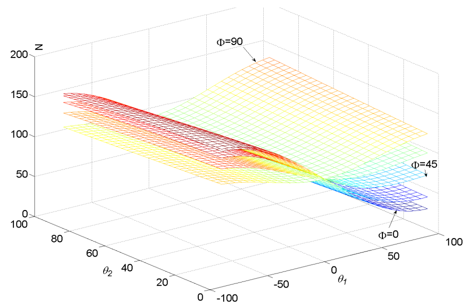

Figure 5: Total force on the spherical joint (*N),* angles are in deg

The force along the *x*-axis depends on the extension without the abduction. That can be explained by the fact that φ is the rotation around x_0. Consequently the variation of φ doesn't affect the component of the load along x_0.

The force along y_0 (vertical component) is negative everywhere. It has a minimum absolute value (maximum algebric) for φ=0, θ_1=π/2, θ_2=0: for this configuration the device is vertical and springs are in rest, the load is the weight only. The force is in its maximum absolute value when φ=0, θ_1=-π/2, θ_2=0: for this configuration the tensions of both springs are maximum vertical and downward. The load is the sum of all the forces. For φ= π/2, the vertical force is constant whatever the values of θ_1 and θ_2. Indeed, when φ= π/2 the device is horizontal and the tilt doesn't change the vertical load. The lengths of both springs remain constant and the vertical load too.

The force along z_0 can be negative or positive depending on θ_1 and θ_2. However the amplitude of this force depends on φ and this force becomes null when φ=0. This force is due to the spring tensions. When φ=0 the device is in the plane (x_0y_0) and there is not any force along z_0. The maximum value of this force is for φ= π/2, θ_1=π/2, θ_2=0. In this case, the device is collinear with z_0, and the tensions of both springs have their maximum horizontal components.

The maps for the norm of the force have a variation similar to the absolute value of the component along y_0. The maximum is reached when φ=0, θ_1=π/2, θ_2=0 but never exactly for these values. In fact, for these value the y_0 component is maximum but not the x_0 and z_0 ones.

IV. Friction effects

To our knowledge, all previous works neglected friction (section II). In this section, the friction effect is modeled. The motion of a handicapped person can be considered as quasistatic. Hence, viscous friction is neglected but dry friction is taken into account. The friction increases the difficulty of motion for the patient, but it decreases the unbalance of the device. In the previous section, we found a specific stiffness for each spring according to each lever arm. We will see in the sequel that a range of stiffness corresponds to each lever arm. In a first assumption, let us consider friction as a constant torque. The forearm is in equilibrium. The acting torque at O_2, along every direction, is less than the friction torque in both ways. The sum of torques applied at O_2 without friction is:

$$\sum \vec{\mu}_{/O_2} = \overrightarrow{O_2G_2}\otimes\left(-m_2\vec{g}\right)+\overrightarrow{O_1f_2^{'}}\otimes k_2\overrightarrow{f_2^{'}f_2}$$
$$=\left(m_2g\frac{l_2}{2}-k_2h_2^2\right)\sin\varphi\sin\left(\theta_1+\theta_2\right)\vec{i}-\left(m_2g\frac{l_2}{2}-k_2h_2^2\right)\cos\left(\theta_1+\theta_2\right)\vec{k} \quad (13)$$

The torque around the axis passing through O_2 is given by:

$$\sum \vec{\mu}_{/O_2}.\vec{z}_2=\left(m_2g\frac{l_2}{2}-h_2^2\right)\cos\left(\theta_1+\theta_2\right)\cos\varphi \quad (14)$$

The forearm is in equilibrium if:

$$-C_2\le\left(m_2g\frac{l_2}{2}-k_2h_2^2\right)\cos\left(\theta_1+\theta_2\right)\cos\varphi\le C_2 \quad (15)$$

$$\Leftrightarrow m_2g\frac{l_2}{2h_2^2}-\frac{C_2}{h_2^2\cos\left(\theta_1+\theta_2\right)\cos\varphi}\le k_2\le m_2g\frac{l_2}{2h_2^2}+\frac{C_2}{h_2^2\cos\left(\theta_1+\theta_2\right)\cos\varphi}$$

We can verify that if the friction is null, equation (15) reduces to equation (11). The arm is in equilibrium if the sum of moments around O_1 is less than the friction torque in all directions. The sum of torques applied at O_1 without friction is:

$$\sum \vec{\mu}_{/O_1}=\overrightarrow{O_1G_1}\otimes\left(-m_1\vec{g}\right)+\overrightarrow{O_1G_2}\otimes\left(-m_2\vec{g}\right)+\overrightarrow{O_1f_1^{'}}\otimes k_1\overrightarrow{f_1^{'}f_1}+\overrightarrow{O_1f_2^{'}}\otimes k_2\overrightarrow{f_2^{'}f_2}$$
$$=\overrightarrow{O_1G_1}\otimes\left(-m_1\vec{g}\right)+\left(\overrightarrow{O_1O_2}+\overrightarrow{O_2G_2}\right)\otimes\left(-m_2\vec{g}\right)+\overrightarrow{O_1f_1^{'}}\otimes k_1\overrightarrow{f_1^{'}f_1}+\overrightarrow{O_1f_2^{'}}\otimes k_2\overrightarrow{f_2^{'}f_2}$$
$$=-\left(m_1\overrightarrow{O_1G_1}+m_2\overrightarrow{O_1O_2}\right)\otimes\vec{g}+\overrightarrow{O_1f_1^{'}}\otimes k_1\overrightarrow{f_1^{'}f_1} \quad (16)$$
$$=\left(\frac{m_1+2m_2}{2}l_1g-k_1h_1^2\right)\left[\sin\varphi\sin\theta_1\vec{i}-\cos\theta_1\vec{k}\right]$$

Two torques have to be considered, the torque around z_2 and the torque around x_0. Taking friction into consideration, the arm is in equilibrium around z_2 if and only if:

$$-C_1\le\left(k_1h_1^2-\frac{m_1+2m_2}{2}l_1g\right)\cos\theta_1\cos\varphi\le C_1 \quad (17)$$

$$\Rightarrow\frac{m_1+2m_2}{2h_1^2}l_1g-\frac{C_1}{h_1^2\cos\theta_1\cos\varphi}\le k_1\le\frac{m_1+2m_2}{2h_1^2}l_1g+\frac{C_1}{h_1^2\cos\theta_1\cos\varphi}$$

The arm is in equilibrium around x_0 if and only if:

$$-C_1\le\left(k_1h_1^2-\frac{m_1+2m_2}{2}l_1g\right)\sin\varphi\sin\theta_1\le C_1 \quad (18)$$

$$\Leftrightarrow\frac{m_1+2m_2}{2h_1^2}l_1g-\frac{C_1}{h_1^2\sin\varphi\sin\theta_1}\le k_1\le\frac{m_1+2m_2}{2h_1^2}l_1g+\frac{C_1}{h_1^2\sin\varphi\sin\theta_1}$$

Without friction, for each h_i corresponds a specific stiffness of the corresponding spring. With friction taken into account, the stiffness can be chosen inside an interval. The width of this interval depends on the configuration of the orthosis. We can see easily that the minimum width is:

$$\frac{(m_1+2m_2)l_1 g-2C_1}{2h_1^2}\le k_1\le\frac{(m_1+2m_2)l_1 g+2C_1}{2h_1^2}$$
$$\frac{mgl_2-2C_2}{2h_2^2}\le k_2\le\frac{mgl_2+2C_2}{2h_2^2} \qquad (19)$$

Stiffness chosen inside these intervals ensures the equilibrium whatever the configuration of the orthosis. We can see that, for $\cos\varphi=0$ and $\sin\theta_1=0$ simultaneously, the device is in static equilibrium whatever the stiffness of both springs. The asked question in the following is: is there a domain of angles where the friction is sufficient for insuring static equilibrium?

The device is in equilibrium without springs if:

$$m_2 g\frac{l_2}{2h_2^2}-\frac{C_2}{h_2^2\cos(\theta_1+\theta_2)\cos\varphi}\le 0$$
$$\frac{m_1+2m_2}{2h_1^2}l_1 g-\frac{C_1}{h_1^2\cos\theta_1\cos\varphi}\le 0 \qquad (20)$$
$$\frac{m_1+2m_2}{2h_1^2}l_1 g-\frac{C_1}{h_1^2\sin\varphi\sin\theta_1}\le 0$$

The limit is when the three equations equal zero, yielding:

$$\sin(2\varphi)=\sin(2\theta_1)=\frac{4C_1}{(m_1+2m_2)gl_1} \qquad (21)$$

Four combinations of solutions can exist:

$$\varphi=\frac{1}{2}Arsin\frac{4C_1}{(m_1+2m_2)gl_1}$$
$$\theta_1=\pm\left(\frac{\pi}{2}-\frac{1}{2}Arsin\frac{4C_1}{(m_1+2m_2)gl_1}\right) \qquad (22)$$
$$\theta_2=\pm\left(Arcos\left(\frac{2C_2}{m_2 g l_2\cos\varphi}\right)-\theta_1\right)$$

According to the physical parameters, we could define the domains where the system is in equilibrium without springs. We can remark that without friction this domain is reduced to the vertical position of the device. In this case three combinations correspond to a non-stable equilibrium (at least one body is above the passive joint) and the fourth to a stable one. To conclude, friction increases the effort required to move the device, but at the same time decreases the unbalance of the device.

V. APPLICATION

Let us consider a system for a handicapped person weighting 80Kg and 1.8m tall. The anthropometry ratios give [26]:

$$m_1=0.028\times 80=2.24Kg$$
$$m_2=0.016\times 80=1.28Kg$$
$$l_1=0.186\times 1.80\approx 0.33m \qquad (23)$$
$$l_2=0.146\times 1.80\approx 0.26m$$

N.B.: Most of the time, these ratios are not respected for handicapped people, and special adjustments are required.

Without friction the relations between h_1, h_2, and k_1, k_2 are:

$$k_1=\frac{5.78}{h_1^2}\qquad k_2=\frac{1.65}{h_2^2} \qquad (24)$$

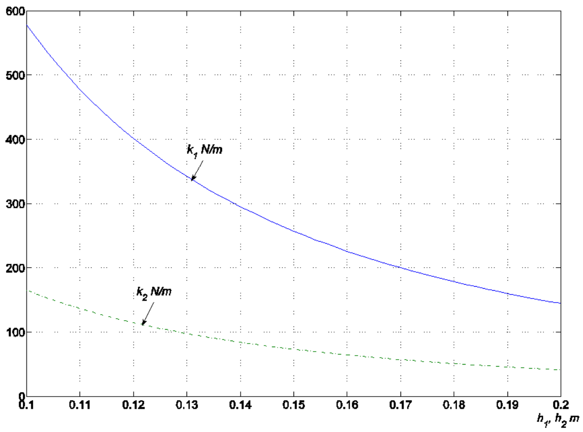

Figure 6: Stiffness of each spring with respect to the corresponding lever arm

Equation (24) gives two curves that can be used to compute h_1 and h_2 according to k_1 and k_2. The design constraint is that each selected spring must have a minimum of elongation equal to twice the corresponding lever arm:

$$\Delta l_i=2h_i \qquad (25)$$

We can use two springs that have the following characteristics:

Table 1: Mechanical characteristics of the springs

Spring	*Stiffness K_i (N/m)*	*Elongation allowed*	*Initial tension F_i(N)*
R_1	*200*	*0.560m*	*1.0*
R_2	*100*	*0.300 m*	*0.276*

For this parameters Equation (24) gives:

$$h_1=\sqrt{\frac{5.78}{202}}=0.169m\quad h_2=\sqrt{\frac{1.65}{100}}=0.128m \qquad (26)$$

Both values are acceptable. Both springs are pre-stressed, and the initial lengths are not null. In order to compute the initial configuration we have to compute the initial elastic potential energy of both springs. This energy is given by the formula:

$$Ep_{i0}=\frac{F_i^2}{2K_i}. \qquad (27)$$

Consequently:

$$Ep_{10}=\frac{1.01^2}{2\times 200}=2.54E-3J$$
$$Ep_{20}=\frac{0.276^2}{2\times 100}=3.8E-4J \qquad (28)$$

We have 2 equations and three unknowns (φ, θ_1, θ_2).

Assuming that φ_0=0, we can compute:

$$\theta_{10} = Arsin\left(1-\frac{Ep_{10}}{h_1^2}\right) = 82.35^\circ$$
$$\theta_{20} = Arsin\left(1-\frac{Ep_{20}}{h_2^2}\right) - \theta_{10} = 0.16^\circ \qquad (29)$$

Based on these values, we designed the CAD model shown on figure 7. This device aims at verifying that static equilibrium is achieved. The spring guides have variable lengths. They are connected to the support and to the moving parts by spherical joints. The design of the real arm orthosis (where the classical spherical joint will be replaced by a joint not interfering with the real shoulder) will be done in further works.

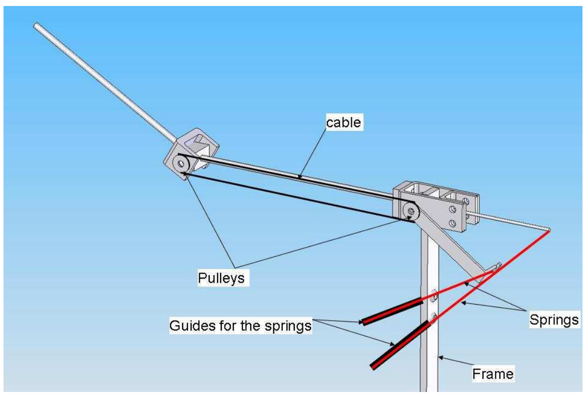

Figure 7: Preliminary CAD for the orthosis

VI. Conclusions and Further Works

In this paper, we have presented the design of gravity balanced device, which can be used as an upper-limb orthosis for an handicapped person. The device is kinematically redundant, because it has five degrees of freedom but three parameters are enough to define its posture. This redundancy allows the patient to use more muscles in his rehabilitation. The device uses two springs and a system of cable-pulleys for gravity compensation. We carried out the dimensioning of the springs, and we enlightened that two springs are sufficient to balance the device. We computed the forces in the spherical joint in order to be able to dimensioning it. We noticed that static friction has two effects. On the one hand, it increases the forces required from the patient to move the device, but on the other hand it makes the design easier as spring rigidity must not be so accurate, and it decreases the unbalance of the device. Finally, a case study was carried out, and numerical computation was done. In this paper, we considered the friction as constant torque, however it is a linear function of the force in every direction. The variations of this torque can give interesting aspects about the balance of the device. Moreover, the deformation of the device were neglected, mostly that of the lever arms. The study of these aspects and the design of a real prototype will be the subject of further works.

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